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WANL-TME-2769
JANUARY 1971

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DATA ITEM S-54

STRUCTURAL SUPPORT COOLANT ASSEMBLY EVALUATIONS (U)

TRADE STUDY NO. 773

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ABSTRACT

This report discusses SSCA requirements under normal and malfunction conditions, leading to permissible leakages, valve rates, and emergency procedures.

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LIST OF ILLUSTRATIONS

1.0 SCOPE

The purpose of this study is to provide the SSCA evaluations necessary to further define the SSCA specification requirements. The study will include sufficient evaluations of the system under normal and malfunction conditions to support the detailed design of the system and its components and to provide the necessary analytical support for Preliminary Design Review (PDR).

The studies are based on the Nuclear Subsystem (NSS) reference design defined by Westinghouse Astronuclear Laboratory (WANL) Layout Drawing 939J740 and the engine system defined by Aerojet Nuclear Systems Company (ANSC) Layout Drawing 1137400-C. The calculational results of the studies are obtained using the PAM [(1)*] digital model and the E-1 CAM[(2)] analog model.

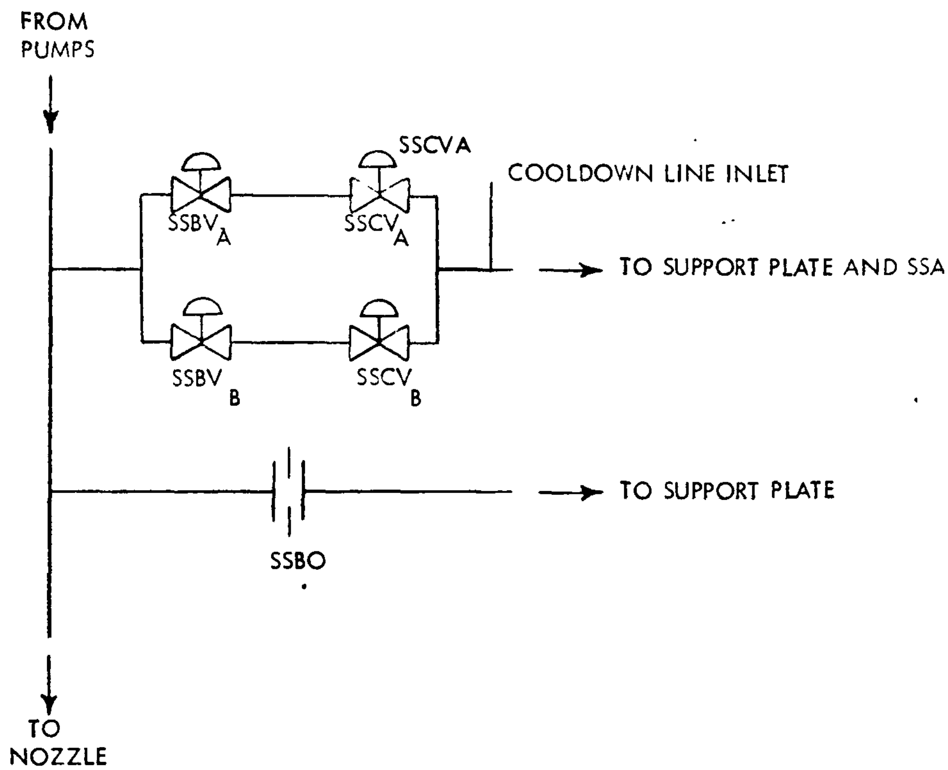
This study is a continuation of Trade Study 760, NERVA Structural Support Coolant Assembly Concept Selection [(3)], and had previously been identified as Phase II of that study. The study is a Category C Trade Study, i.e., required for NSS PDR, and, though not lending itself to the S-054 Trade Study format, will be presented as an S-054 report [(4)].

* Superscript numbers refer to references in Section 6.0.

2.0 REQUIREMENTS FOR SSCA PERFORMANCE

Trade Study 760 selected an SSCA concept based on an initial set of requirements. These requirements were subsequently changed by government directive and the changes incorporated into the NSS Specification CP-677555A and the SSCA Specification EC677575.

Following the presentation of Trade Study 760 in February, 1970, five Government directives have influenced the design of the Structural Support Coolant Assembly (SSCA). Technical Directive 70-26[5] stated, "The structural support system shall consist of a four-valve system (active redundancy) with orificed bypass flow. The effect of the flow swing (nozzle) needs reconfirmation assuming $1.00 corrosion loss at rated conditions (EOL) and no drum movement to achieve throttling." This direction was confirmed by Change Order 70-8[6]: "The engineering program for the structural support system shall consist of a four (4) valve system (active redundancy) with orificed bypass flow." Supplemental information to Change Order 70-8[7], stated, "... no further effort should be devoted to the three-way valve system for the SSCS. ... future efforts should be concentrated on the concept employing pump discharge control valves." The concept employing a pump discharge control valve was included in the reference design by Change Order 70-14[8]: "Provisions shall be made to provide a digital increase in impedance in the pump discharge line of approximately 60 psi at 60% of rated power to achieve stem reactivity requirements for throttling. This additional impedance can obviously be utilized to assist startup and shutdown." The throttle point was changed and the pump discharge valve removed by Change Order 70-24[9]: " ... modify the engine flow schematic... by deleting lines and valves which were previously included to provide part power reactivity without drum motion at end of life. The requirement for 60% power throttle point is changed to a 65% power throttle point and drum motion to achieve the throttle point will be allowable, if necessary." Thus the system studied is compatible with Change Order 70-24 and consists of a four-valve arrangement (active redundancy) with an orificed bypass flow[10] to aid in cooling the support plate. The SSCA is shown schematically in Figure 2-1.



NOMENCLATURE:

SSCV	-	STRUCTURAL SUPPORT COOLANT VALVE
SSBV	-	STRUCTURAL SUPPORT BLOCK VALVE
SSBO	-	STRUCTURAL SUPPORT BYPASS ORIFICE
SSA	-	SUPPORT STEM ASSEMBLY
SSCVA	-	STRUCTURAL SUPPORT COOLANT VALVE ACTUATOR

FIGURE 2-1

Structural Support Coolant Assembly Schematic

3.0 DESCRIPTION OF ANALYSIS APPROACHES

3.1 INTRODUCTION

Trade Study 773 is the second phase of a continuing effo · to further define the SSCA specification requirements and demonstrate system performance. A number of studies lead to selected valve rates, emergency procedures, and permissable leakages. Section 3.0 will present the method of analysis employed in each of the studies. Section 4.0 will present the results of the individual studies. Section 5.0 presents the conclusions resulting from the evaluations.

The analyses are performed using the July 1, 1970, PAM digital model and the E-1CAM analog model, Revision 5A, the most recent version of CAM prior to incorporation of the in-line control features required by Technical Directive 71-8 [11].

For the purposes of this study, start-of-life (SOL) is taken to be the minimum support stem flow case (nominal SOL minus uncertainties); end-of-life (EOL) is taken to be the maximum support stem flow case (nominal EOL plus uncertainties).

3.2 SSCA REQUIREMENTS FOR NORMAL OPERATIONS

3.2.1 Leakage Requirements

Maximum allowable SSCV and SSBV leakages for cooldown and normal operation are discussed and established.

3.2.2 Minimum SSCV Rate for Throttling

The PAM model is used to find the minimum SSCV rate resulting from the 50 $\pm$ 10 psi/sec throttling requirement [12].

3.3 SSCA REQUIREMENTS FOR MALFUNCTION CONDITIONS

Transient malfunction analysis was performed on the analog computer using the E1-CAM Model, Revision 5A, using the SSCV characteristic specified in Figure 4-9. Controllers for E1-CAM were supplied by the NERVA Integrated Instrumentation and Controls Organization (NIICO) and are discussed in the I and C Analysis Report for NSS PDR (S-102A).

3.3.1 Maximum SSCV Rate due to SSCV Malfunction

SSCV failures closed at SOL and EOL are studied to set the maximum permissible SSCV failure rate. A sample run is analyzed to show the effects of the failure, followed by a cross-plot of the rate of change of chamber temperature as a function of SSCV rate. The SSCV maximum rate set by failures is based upon this plot.

3.3.2 SSBV Rates

SSCV malfunctions open at SOL are studied to find the minimum SSBV closure rates necessary to protect the NSS. A sample run is presented to show the sequence of events. A cross-plot of the rate of change of chamber temperature as a function of SSBV rate is used to find the SSBV rate necessary for protection from an SSCV malfunction.

The concept of position demand steps is introduced and discussed. Failures of the SSBV closed are studied to find the limits on SSBV rates. After presenting a sample run to show the sequence of events, cross-plots of the initial chamber temperature rate response and the recovery rate response are presented and used to set the limits on the SSBV failure rate.

3.3.3 Single Turbopump Operation

SSCA profiles for startup, shutdown, and throttling operations with a single operational turbopump are discussed in Section 5.1 of the NSS Systems Analysis Summary Report[13].

3.4 SSCV STATIC OPERATING RANGE

The static operating range requirements are reviewed for various modes of system operations.

4.0 DISCUSSION OF RESULTS

This section contains the results of analyses leading to the SSCA specification values of allowable leakage, valve rates, and position-demand steps and timing for malfunction recovery procedures.

4.1 SSCA REQUIREMENTS FOR NORMAL OPERATION

4.1.1 Leakage Requirements

No shutoff capability of the SSCV is required during normal operation. In the event an SSCV fails in the open position, the SSBV must reduce the flow in that leg to bring the total SSA flow within the operating range of the remaining SSCV. This flow is one-half the minimum SSA flow, or 2.6 lb/sec.

During cooldown operations, the allowable leakage is determined by the amount of flow permitted to bypass the stems during the "stem flow only" phase of cooldown. The flow is not lost but lowers chamber temperature, reducing cooldown efficiency. The maximum permissable leakage case occurs when the total core flow is sufficient to remove the minimum decay power during the "stem flow only" phase. The maximum leakage flow is found to be 0.22 lb/sec

ANSC, with WANL approval, has apportioned the leakage flows equally to the SSCV and SSBV:

Normal Operations - Allowable Leakage	
Closed SSCV - (with SSBV open):	2.6 lb/sec
Closed SSBV - (with SSCV open):	2.6 lb/sec
State Points	
SSCA Inlet Pressure:	1320 psia
SSCV/SSBV P:	2.6 psia
SSCA Inlet Temperature:	$59^{o}R$
Fluid - Hydrogen	

Cooldown Operations - Allowable Leakage

Closed SSCV - (with SSBV open):	0.11 lb/sec
Closed SSBV - (with SSCV open):	0.11 lb/sec
State Points	
SSCA Inlet Pressure:	30 psia
SSCA Inlet Temperature:	$40^{o}R$
SSCA ΔP:	20 psia
Fluid - Hydrogen	

4.1.2 Minimum Required SSCV Rate

The minimum SSCV rate is set by the 50 $\pm$ 10 psi/sec throttling maneuver. The maximum SSCV velocity required during a throttling transient occurs at EOL with one operating SSCV. This results from the largest flow swing required of one SSCV operating in a region of lowest gain. The maximum rates, obtained from PAM data(15), are:

Graphite Core : 13.2 degrees/second nominal throttling
15.9 degrees/second maximum throttling

Composite Core: 14.4 degrees/second nominal throttling
17.3 degrees/second maximum throttling

Since the SSCA is identical for both cores, 14.4 degrees/second is the minimum SSCV velocity for throttling at 50 psi/second. For throttling at specification extreme, 60 psi/second, 17.3 degrees/second is the minimum SSCV velocity.

4.2 SSCA REQUIREMENTS FOR MALFUNCTION CONDITIONS

A parametric study of SSCV rates, SSBV rates, and emergency procedures, i.e., position demand steps and timing, was made to define specification values acceptable under malfunction conditions.

4.2.1 Maximum SSCV Rates Under Malfunction Conditions

The maximum SSCV rate is set by malfunctions in which the SSCV ramps closed at its maximum velocity at EOL. A typical transient is shown in Figure4-1. The following sequence of events, keyed to Figure4-1, occurs:

(1) $SSCV_A$ begins to ramp closed at an assumed maximum rate of 40°/sec. (Figure 4-1, Channel 1), decreasing the flow through that leg of the SSCA (Figure 4-1, Channel 4) and causing a corresponding loss of reactivity which reduces chamber temperature (Figure 4-1, Channel 6).

(2) 0.1 second after the start of the malfunction, $SSBV_A$ begins to close at 50%/sec. (Figure 4-1, Channel 3).

(3) $SSCV_B$, remaining in chamber temperature control, opens (Figure 4-1, Channel 2) to restore the support stem flow (Figure4-1, Channel 5) returning chamber temperature to its steady-state value (Figure4-1, Channel 6).

This run illustrates the need for a faster increase of flow in the unfailed leg of the SSCA. Without some means of increasing flow, e.g. a step in position demand to $SSCV_B$, chamber temperature decreases too fast in the interval between the time $SSCV_A$ decreases the flow and the time $SSCV_B$ can restore it.

A series of analog computer runs was performed to show the effect of SSCV closure rate at SOL and EOL. The same general response discussed above occurs in each transient. The rate of change of chamber temperature is the important variable because of its $\pm 175^\circ$R/sec. limit. Figure 4-2 shows the response of chamber temperature rate to various SSCV closure rates. The SOL case presents no problem because the temperature controller used in E1-CAM can quickly restore the support stem flow. At EOL, the chamber temperature exceeds its rate limit for SSCV rates above 22.5°/sec.

For faster SSCV rates, the excessive chamber temperature transient occurs in the interval between the time $SSCV_A$ reduces the support stem flow and the time $SSCV_B$ can restore it. The SSBV rate can aggrevate the problem by stopping the flow in the malfunctioned leg of the SSCA even faster. The analysis shown in Figure 4-2 was performed with an SSBV rate of 50%/sec. Further analysis of SSBV rates showed 50%/sec. to be too low; therefore, the SSBV should not be signaled closed until the failed SSCV has closed.

The SSCV rate for inclusion in the SSCA specification is chosen as 18 degrees/second minimum, 22 degrees/ second maximum. The minimum rate is based on the throttling requirement for normal operations, the maximum rate is based on the requirement to limit chamber temperature response under malfunction conditions.

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4.2.2 SSBV Rate Limits

A series of analog computer runs was made to determine the structural support block valve rate limits. A minimum rate to protect against opening malfunctions of the SSCV is found from these runs and discussed in Section 4.2.2.1. Analysis of the runs indicates a step in the SSCV position demand should be incorporated in the emergency procedure for this malfunction. The step demand is discussed in Section 4.2.2.2. The chamber temperature response to an SSBV failure leading to maximum and minimum SSBV rates for that condition is discussed in Sec tion 4.2.2.3.

4.2.2.1 SSBV Response Rates for an SSCV Open Malfunction

During the course of the parametric study, the worst-case malfunction of the SSCV influencing the SSBV response rate proved to be an opening of the SSCV from SOL, rated conditions. Limiting variables were stem liner temperature and rate of change of chamber temperature. A typical run is shown in Figures 4-3 and 4-4. The following sequence of events, keyed to Figures 4-3 and 4-4, occurs.

1) $SSCV_A$ starts failing open at 15°/sec. (Figure 4-3, Channel 1), adding reactivity and causing chamber temperature to rise (Figure 4-3, Channel 6).
2) $SSCV_B$, remaining in normal temperature control, begins to close (Figure 4-3, Channel 2) to reduce the chamber temperature error (Figure 4-3, Channel 6) resulting from the reactivity insertion caused by $SSCV_A$.
3) After 0.1 seconds, $SSBV_A$ starts to close at its maximum rate, 66-2/3%/sec. in this case (Figure 4-3, Channel 3).
4) As $SSBV_A$ shuts off the flow in the failed leg of the SSCA (Figure 4-3, Channel 4), $SSCV_B$ must reverse direction (Figure 4-3, Channel 2) to return the support stem flow to its original value (Figure 4-3, Channel 5). At this time the loss of reactivity caused by $SSBV_A$ closing causes the chamber temperature transient to reverse direction with a rapid decrease in temperature (Figure 4-3, Channel 6).

CRD 5) The support stem liner temperature (Figure 4-4, Channel 4) is initially at its steady state limit, 1160°R. As $SSCV_A$ opens, the liner temperature decreases. The liner temperature reverses and begins to rise as $SSBV_A$ shuts off the flow in that leg. As $SSCV_B$ restores the flow, the liner temperature returns to its steady-state value. The liner temperature reaches, but does not exceed, its transient limit, 1320°R.

The initial rate of change of chamber temperature discussed in (2), is shown in Figure 4-5 as a function of block valve rate. The negative temperature rate, discussed in (4), is shown in Figure 4-6. Figure 4-6 indicates 80%/sec. is the minimum SSBV closure rate necessary to avoid violation of the -175°R/sec. limit. The high SSBV rate causes the flow in the failed leg to be shut off almost immediately so the initial rise in chamber temperature is small, resulting in a less severe demand to reduce the chamber temperature and keeping the fast negative transient within limits.

4.2.2.2 Introduction of Steps in SSCV Position Demand

The addition of a positive step in position demand to the SSCV in the operating leg of the SSCA may be required to decrease the magnitude of the chamber temperature resulting from the SSCV failing open. See Section 4.2.2.1 for discussion of this failure. The objective is to reduce the initial rise in chamber temperature by fast SSBV action followed by a flow increase in the operating SSCA leg to keep the chamber temperature from under-shooting. A new operating profile for the single SSCA leg is required after the transient. The step just switches to this new profile more quickly and involves controller logic. The magnitude and introduction time of the step must be tailored to the malfunction. If the step is introduced too soon, the magnitude of the initial rise in chamber temperature will be increased. If the magnitude of the step is too great, a secondary overshoot of chamber temperature causes problems. The magnitude of the step is determined by the need to double the flow through the single SSCV that remains operating, and the timing is tailored to the individual malfunction. As the design of the chamber temperature controller matures, the magnitude and timing of the step should be refined.

For this study, the following delays were found to produce acceptable transients:

> At throttled conditions, the step is introduced 0.1 second after the start of the malfunction at both SOL and EOL. At rated conditions, the step is introduced 0.1 second after the start of the malfunction for SSCV and SSBV closures at SOL and EOL. The step is delayed 1.0 second for SSCV openings at SOL and 0.5 second for SSCV openings at EOL.

4.2.2.3 SSBV Rates Based on SSBV Closure Malfunctions

Maximum and minimum velocity limits on SSBV closing malfunctions are established in this section. The worst case of malfunctions was found to be closures of an SSBV at EOL, rated conditions. Typical transients are shown in Figure 4-7. The sequence of events, keyed to Figure 4-7, is:

(1) $SSBV_A$ ramps closed at its maximum rate, 100%/sec in this case (Figure 4-7, Channel 3).

(2) A 20° step in position demand is given to the SSCV 0.1 second after the start of the malfunction.

(3) As $SSBV_A$ shuts off the flow in the malfunctioned leg of the SSCA, the flow in the other leg rises to restore the stem flow to its initial value (Figure 4-7, Channels 4 and 5).

(4) As the SSCV's open, the chamber temperature rises until the block valve stops the flow in the malfunctioned leg. When $SSBV_A$ stops the flow, the reactivity loss returns the chamber temperature to its steady state value (Figure 4-7, Channel 6).

Figure 4-8 shows the chamber temperature rate response as a function of block valve closing rate. The response results from one of two effects. The first effect occurs for SSBV rates less than 140%/sec. Here the initial positive response shows the step magnitude is too large for low SSBV velocities and results in negative recovery rates when $SSBV_A$ finally stops the flow and the temperature controller demands a decrease in chamber temperature. The second effect occurs at SSBV rates above 140%/second. Here the chamber temperature initial response rate is negative because of the reactivity loss in the stems that occurs before the step demand becomes effective in restoring the SSA flow. The step demand with the normal control causes temperature overshoot and positive temperature recovery rates.

The dashed portion of the recovery curve indicates negligible temperature overshoot for SSBV rates 125 - 140%/second.

The acceptable SSBV closure time is 0.8 ± 0.2 seconds as a result of these data.

4.3 STATIC SSCV IMPEDANCE CHARACTERISTICS

The SSCV impedance characteristic used in this study is shown in Figures 4-9 and 4-10. This impedance characteristic is a requirement of the SSCV Specification EC-90192 and is derived from the state point requirements of section 5.4 of the NSS Systems Analysis Summary Report, S-001.

Static operating points for various system modes are obtained from the composite core state points and noted on the figures to show regions of operation. Figure 4-9 shows the regions of operation for dual turbopumps with one and two SSCA's for SOL and EOL at rated and 65% throttle points. Also shown is the specification minimum SOL point at rated conditions and the specification extreme maximum at EOL throttle conditions. Figure 4-10 shows the regions of operation for a single turbopump with one and two SSCA's for SOL and EOL at the 80% thrust point and the 65% throttle point.

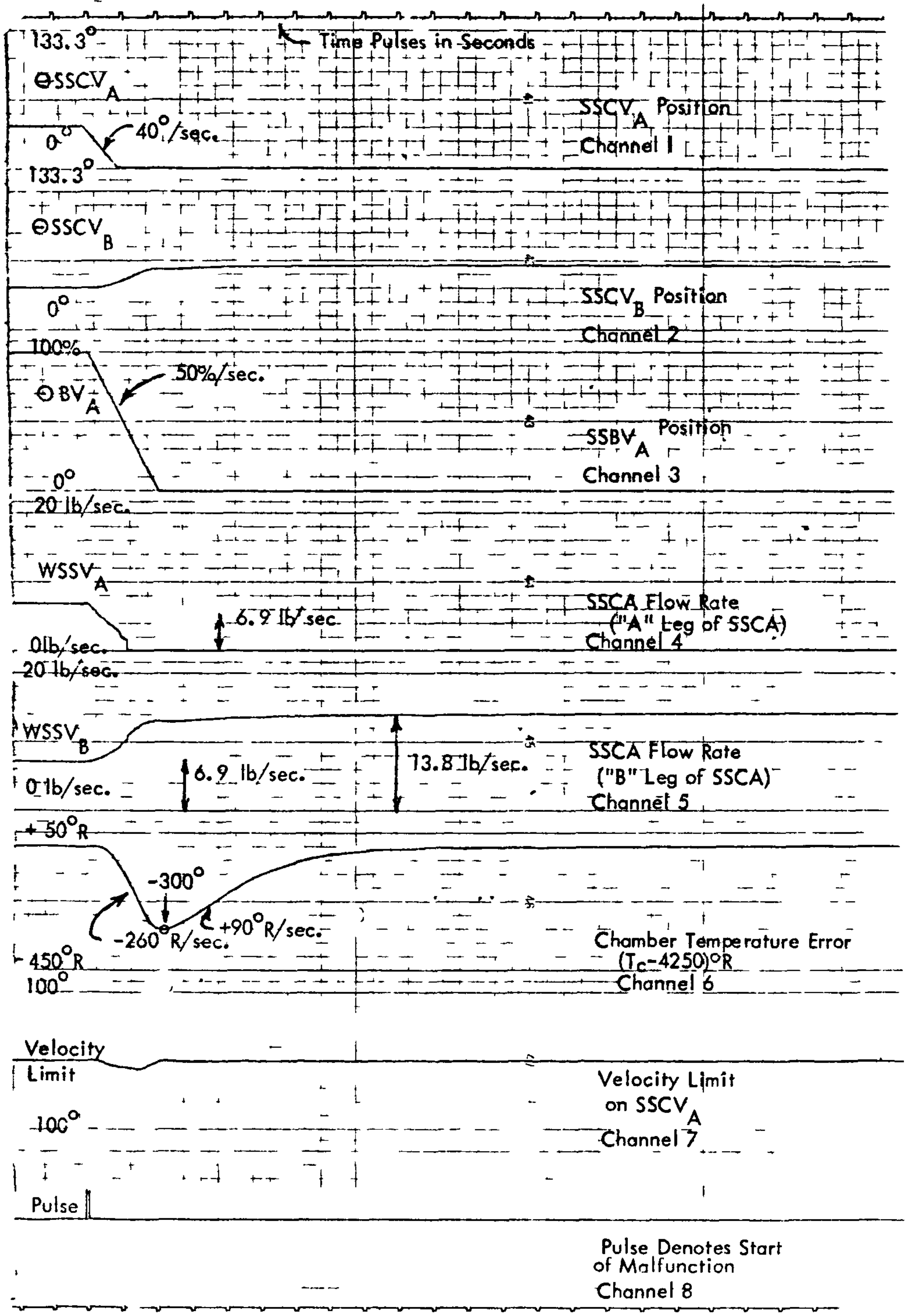

Figure 4-1. $SSCV_A$ Fails Closed at EOL

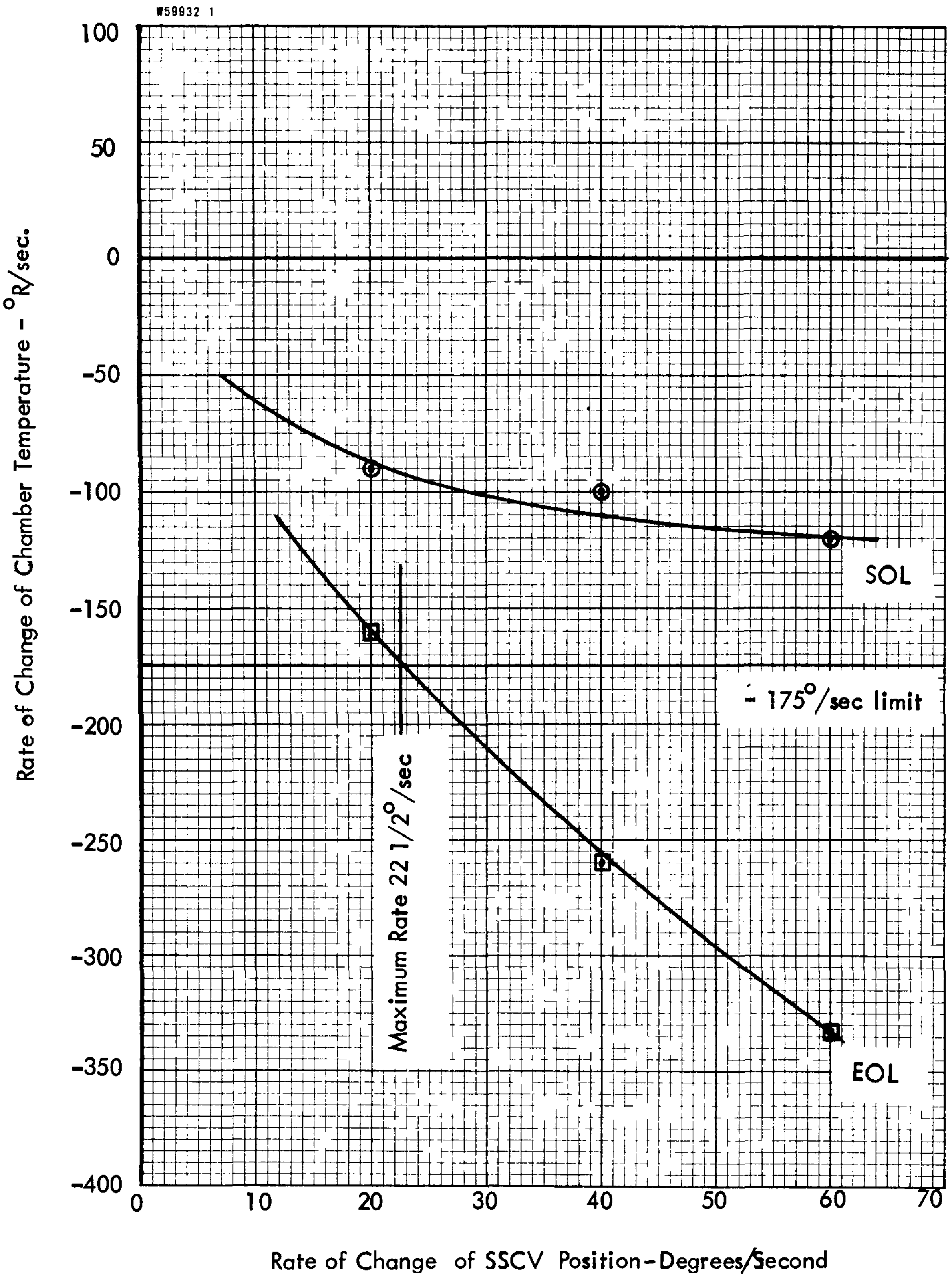

Figure 4-2. Chamber Temperature Rate in Response to an SSCV Closure

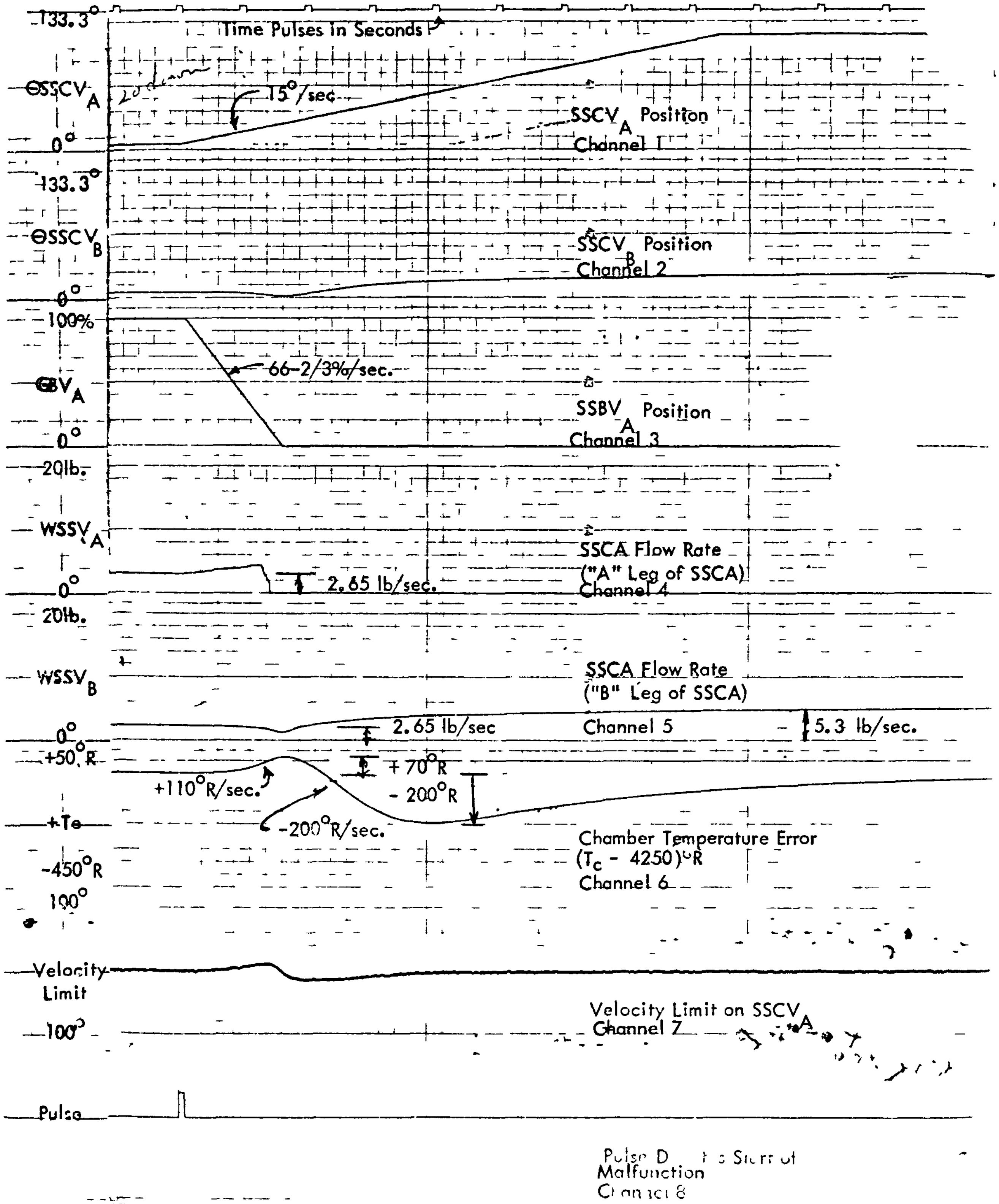

Figure 4-3. $SSCV_A$ Fails Open at SOL

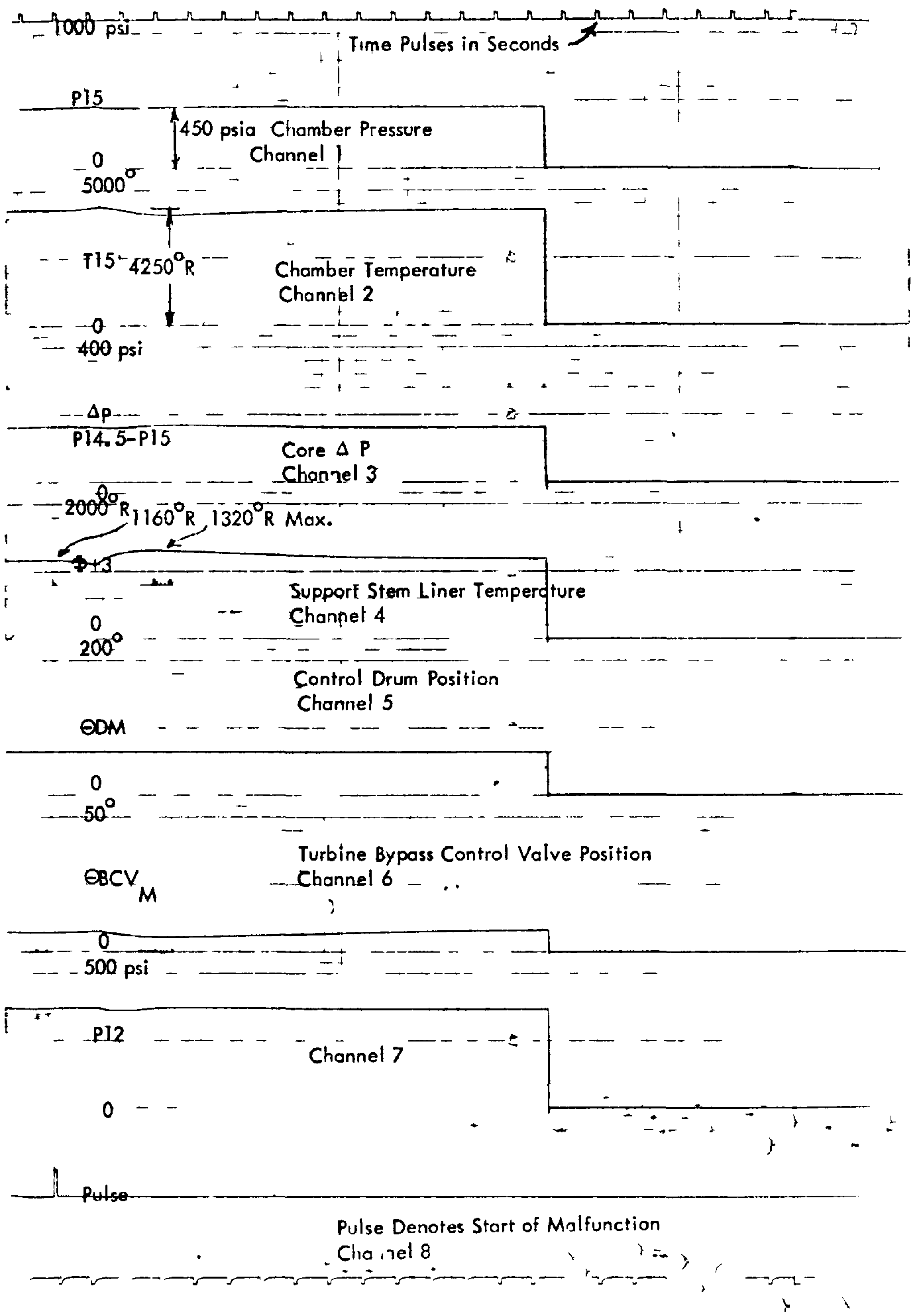

Figure 4-4. $SSCV_A$ Fails Open at SOL

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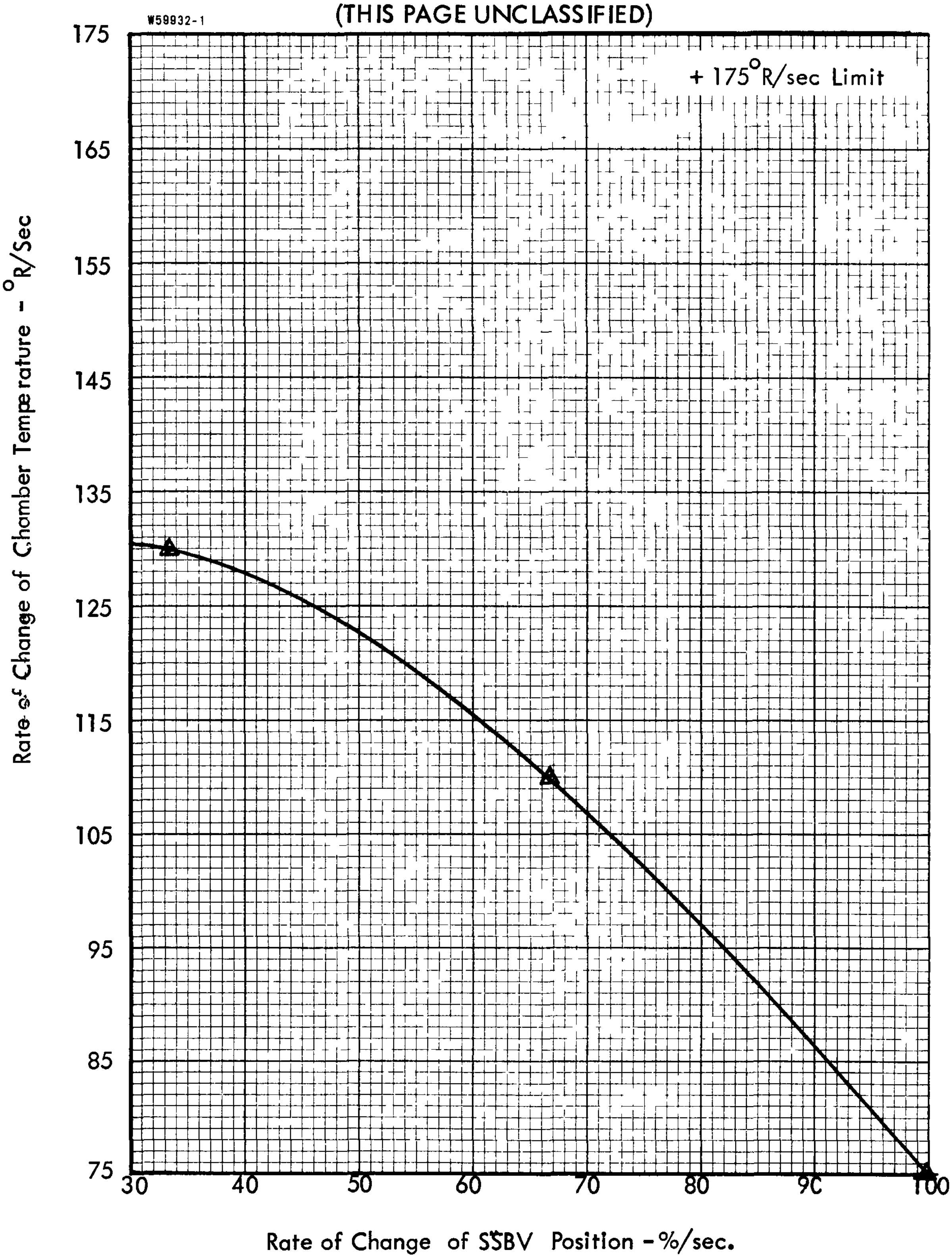

Figure 4-5. Chamber Temperature Rate in Response to SSCV Openings at SOL

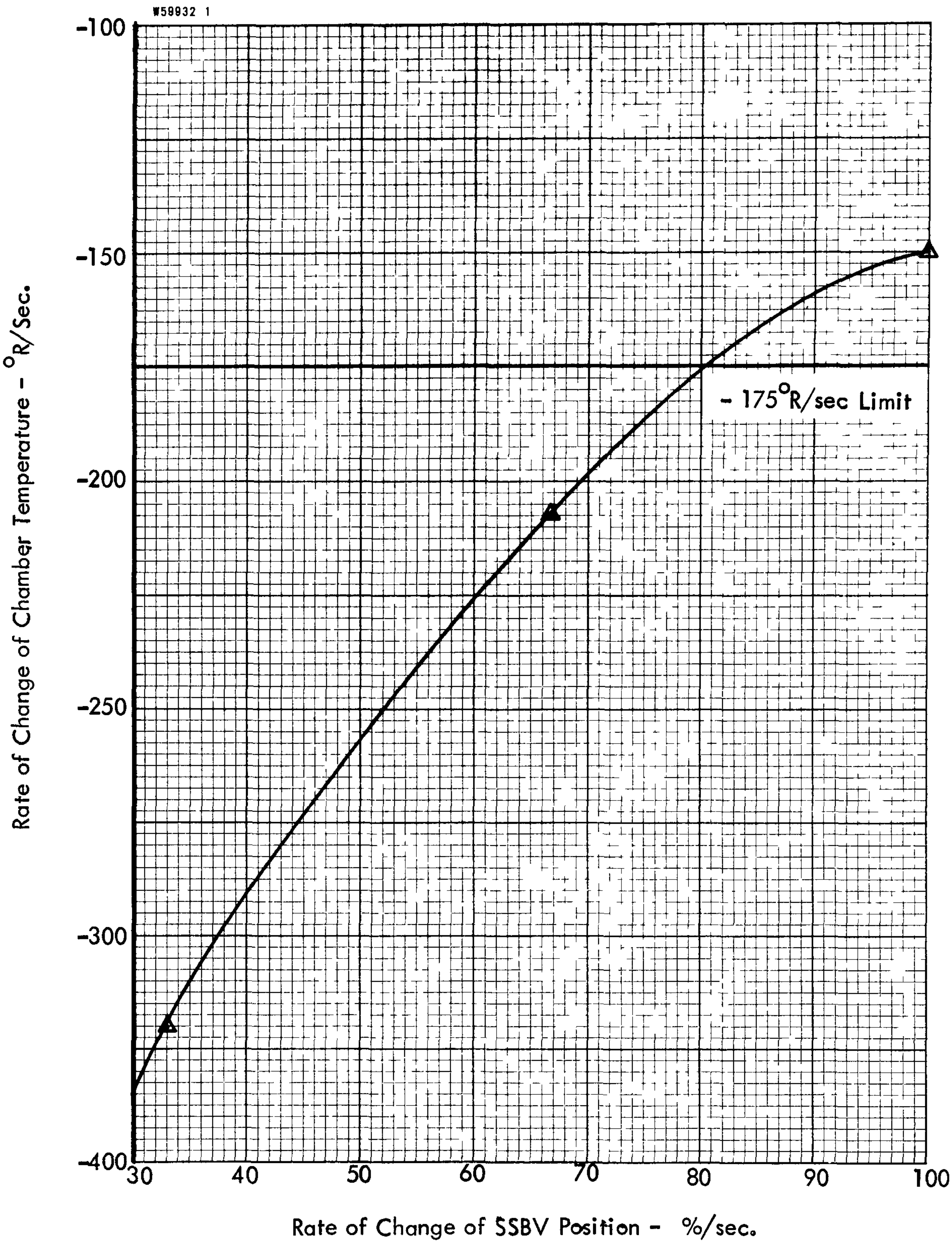

Figure 4-6. Chamber Temperature Rate in Response to SSCV Openings at SOL

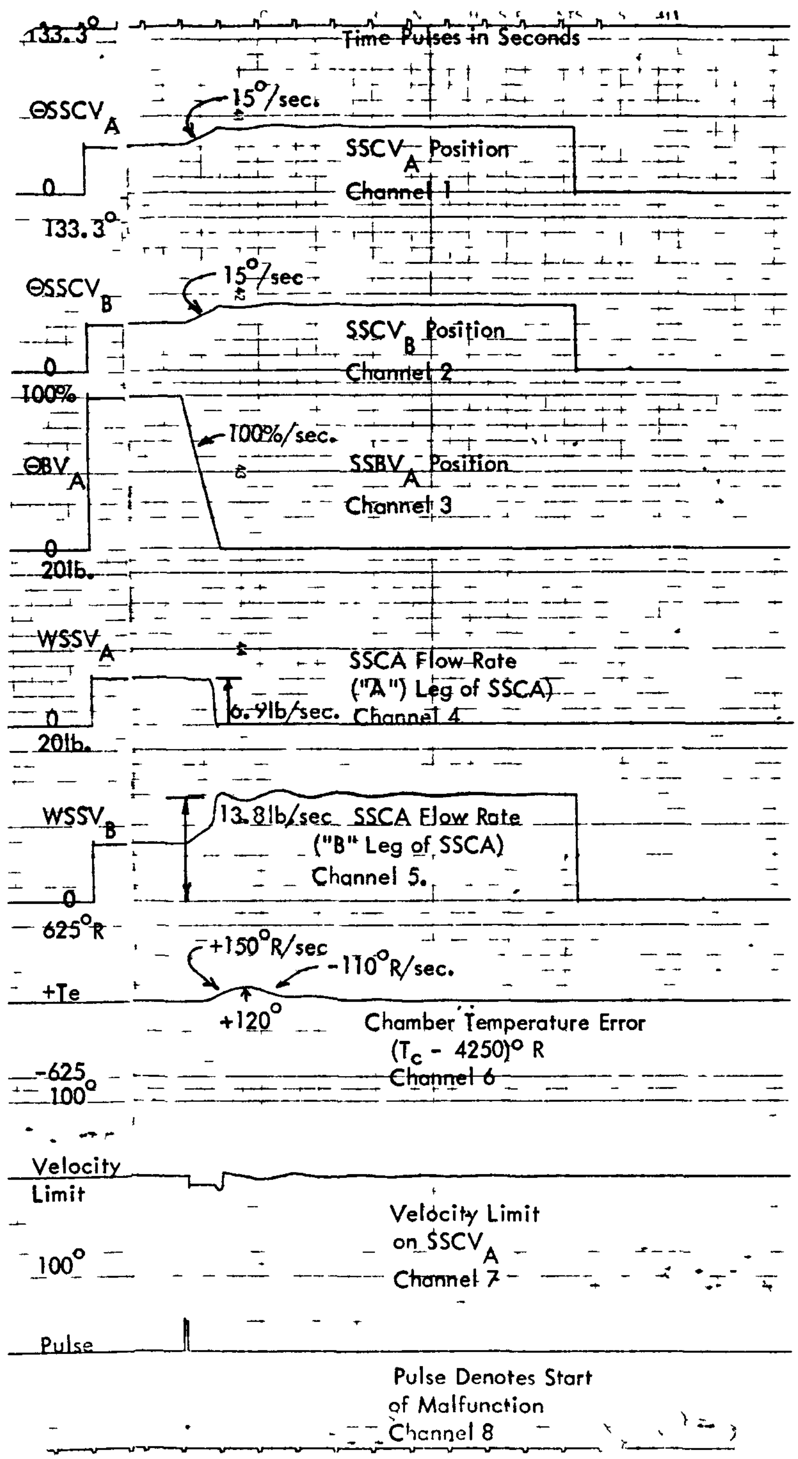

Figure 4-7. $SSBV_A$ Fails Closed at EOL

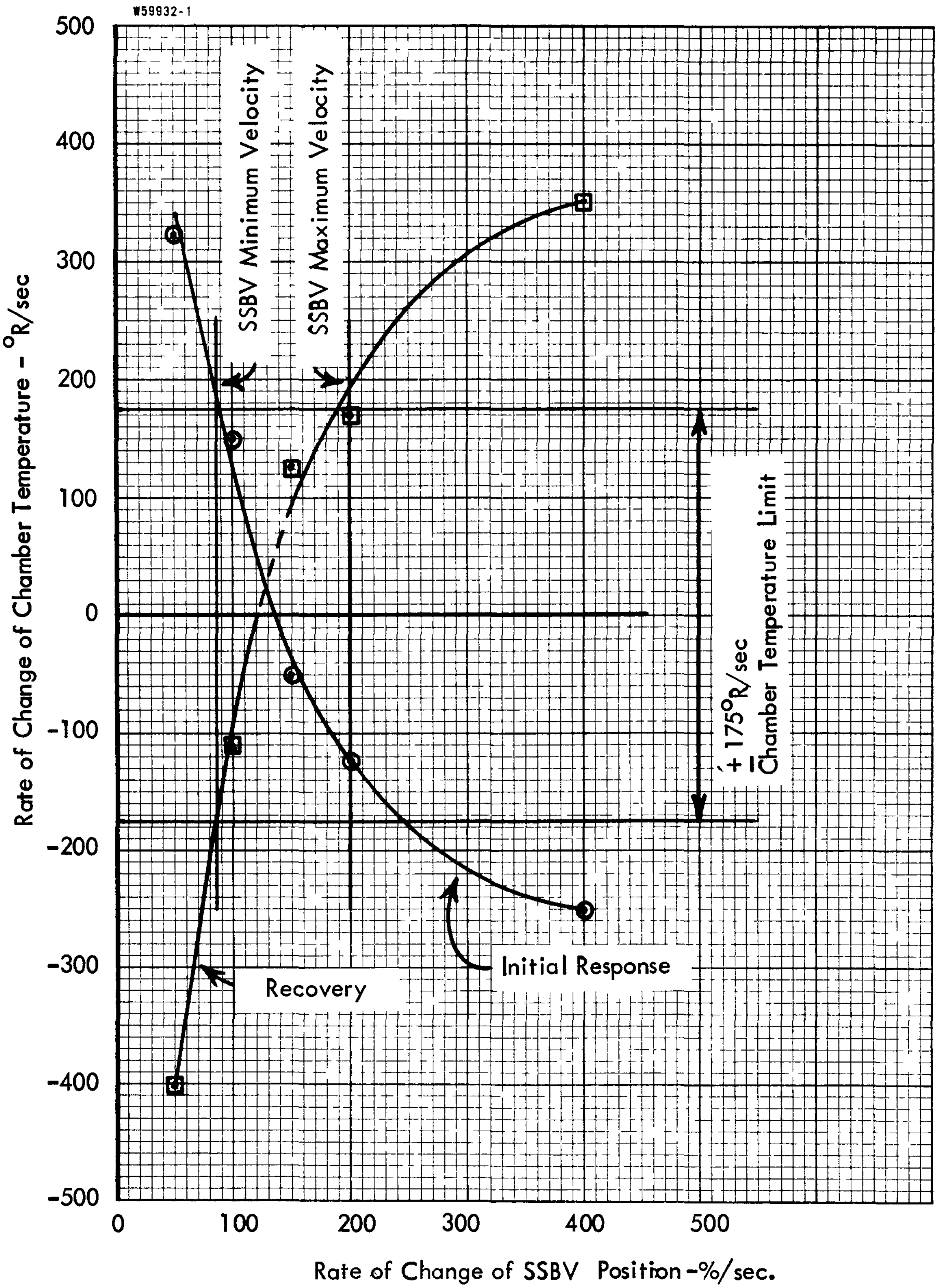

Figure 4-8. Chamber Temperature Rate in Response to SSBV Closures at EOL

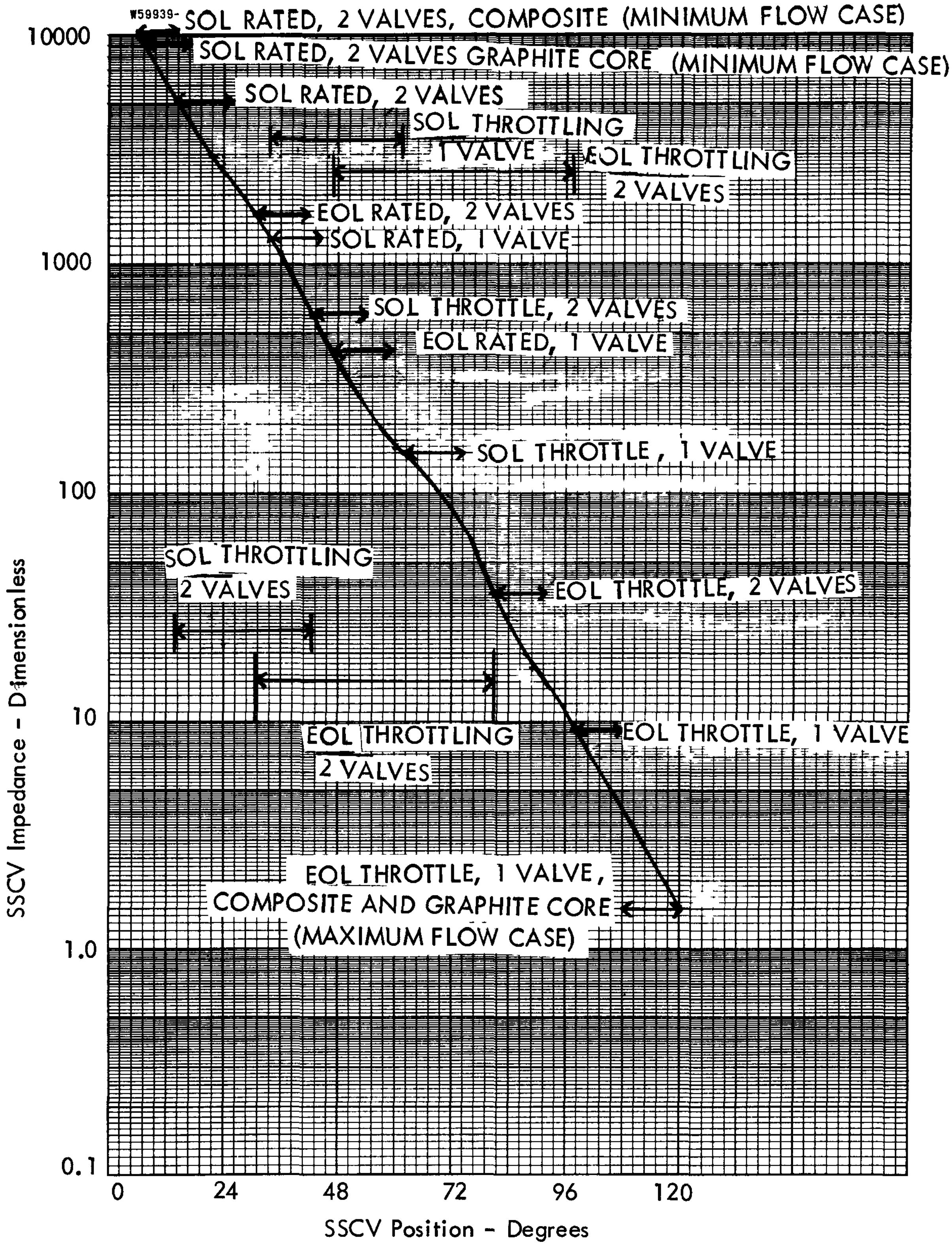

Figure 4-9. Static SSCV Impedance Characteristic

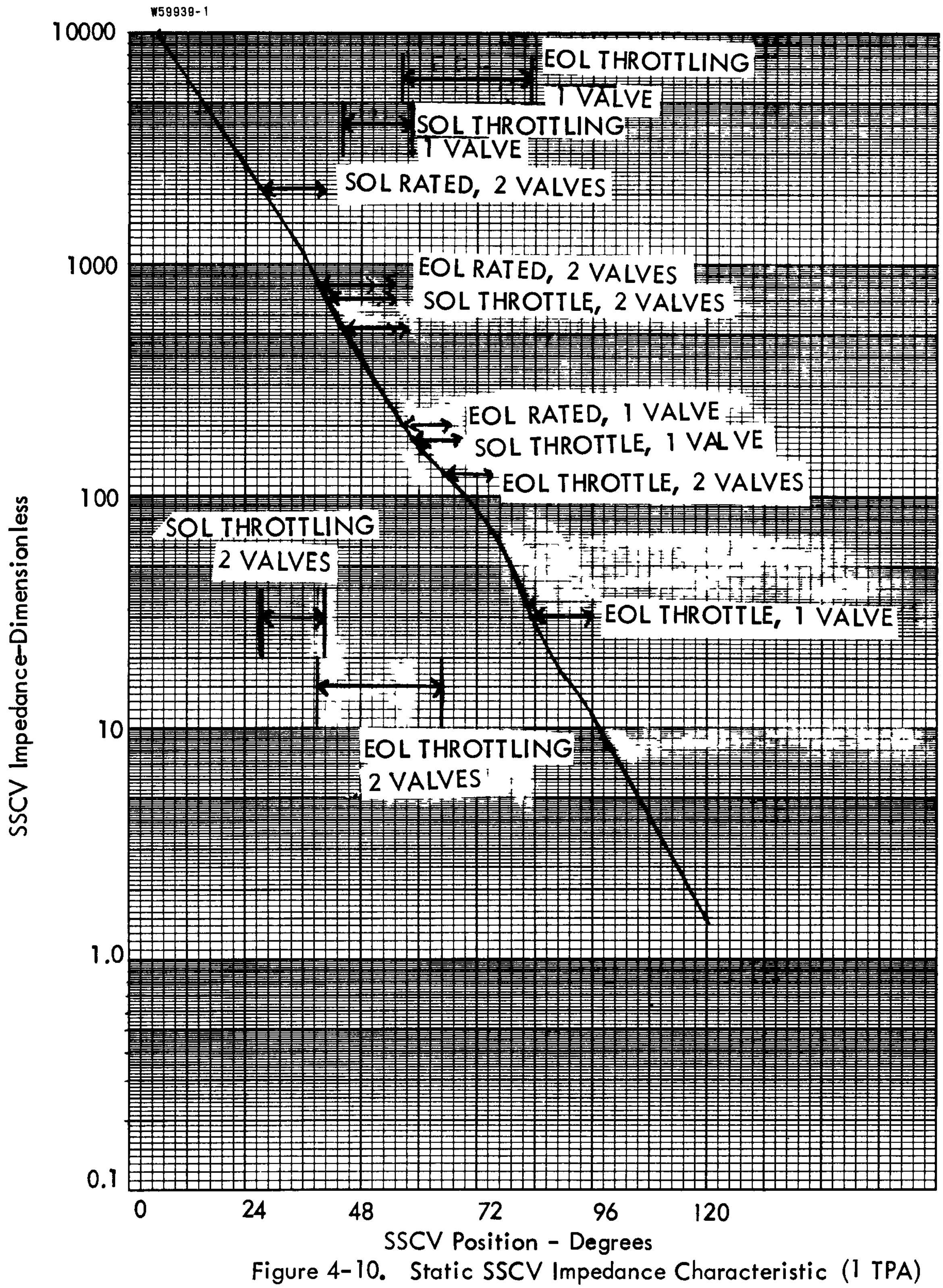

Figure 4-10. Static SSCV Impedance Characteristic (1 TPA)

5.0 SUMMARY AND CONCLUSIONS

Valve rates and leakage requirements discussed in Section 4.0 are presented in Table 5-1 with the selected specification values. These values, in conjunction with the static operating range discussed in Section 4.3, insure proper operation of the SSCA under normal and malfunction conditions. Proper operating procedures under malfunction conditions are essential to this end and will be presented in subsequent discussion. The procedures evolved in the course of the malfunction analyses discussed in Section 4.0 and satisfy the requirement that the SSCA be capable of correcting malfunctions within itself (active redundancy).

In the event that an SSCV failure closed is detected, a positive position-demand step should be given to the operating SSCV. In addition, it is advisable to close the block valve in the failed leg of the SSCA to guard against the failed SSCV inadvertantly opening and inserting excess reactivity. The block valve should not be closed until the SSCV is closed. The position step will cause the operating SSCV to start opening at its maximum rate to avoid an excessive negative chamber temperature transient from reactivity loss at both SOL and EOL. The step will also protect from excessive support stem liner temperature transients at SOL.

If an SSCV fails open, the following procedure should be observed:

1) Command the series block valve to close as soon as the malfunction is detected.
2) After a delay-time keyed to the initial valve position, introduce a positive step-demand to the operable SSCV to protect against excessively negative chamber temperature transients when the block valve closes.

Timing of the SSCV position-demand step should be refined as the chamber temperature controller design matures. If possible, it seems desirable to close the malfunctioned SSCV after its block valve is closed, reducing the leakage through the failed leg of the SSCA.

If an SSBV fails closed, the following procedure should be observed:

1) Upon detection of the failure, introduce a step in position demand to the SSCV in the operable leg of the SSCA.
2) It appears advisable to command the SSCV closed in the failed leg to protect against the failed SSBV reopening.

Throughout the analysis, the impedance characteristic of the block valve caused problems. Virtually no blocking effect is felt as the valve closes until it reaches the point where it is about 70% closed. Upon reaching this point, the flow is completely shut off in less than three-tenths of a second. Needless to say, if the flow is large through that leg of the SSCA, e.g., five or six pounds per second near end-of-life at rated conditions, the system receives quite a shock when the valve closes. The sudden loss in support stem reactivity causes excessively negative chamber temperature transients and requires the introduction of position-demand steps to avoid violation of the rate-of-change of chamber temperature limit. If the block valve impedance changed more gradually with valve position, the possibility exists that the minimum rate requirement could be considerably relaxed.

TABLE 5-1

SUMMARY OF RESULTS AND SPECIFICATION VALUES

SSCV RATE

	Minimum	Maximum
Throttling Requirement (60 psi/sec.)	17.3°/sec.	Not Applicable
Malfunction Protection Requirement	Not Applicable	22.5°/sec.
Selected Specification Rate Requirement	18°/sec.	22°/sec.

SSBV CLOSURE TIME

	Maximum	Minimum
SSCV Malfunction Protection Requirement	1.25 sec.	0.5 sec. (Estimated)
SSBV Malfunction Protection Requirement	1.18 sec.	0.5 sec.
Selected Specification Closure Time	0.8 ± 0.2 sec.	

MAXIMUM VALVE LEAKAGE

	Normal Operations	Cooldown
SSCV	2.6 lb./sec.	0.11 lb./sec.
SSBV	2.6 lb./sec.	0.11 lb./sec.
Valve ΔP, Psia	ΔP - 216 Psia	ΔP - 20 Psia

6.0 REFERENCES

1. DRM-52948, Model Description of the July 1, 1970, PAM, November 19, 1970

2. DRM-51437, Revision B, 10-Hour NSS Portion of the Common Analog Model (This DRM, defining NSS input to E-1 CAM, Revision 6, was renumbered to be E-1 CAM, Revision 5A, by DRM-51437, Revision C.)

3. WANL-TME-2700, Data Item S-54, NERVA Structural Support Coolant Assembly Concept Selection, Trade Study 760 - Phase I, July 1970

4. SNPO-C Letter PPO:PSR, dated March 4, 1970, R. W. Schroeder to A. L. Feldman (ANSC); Subject: Maturity of Data Items for NSS and NSS Components Design Preliminary Design Review

5. SNPO-C Letter SD:AAM, dated March 6, 1970, R. W. Schroeder to A. L. Feldman (ANSC); Subject: Technical Directive No. 70-26

6. Technical Directive 70-26, March 9, 1970

7. SNPO-C Letter OCTO:LCC, dated April 14, 1970, R. W. Schroeder to A. L. Feldman (ANSC); Subject: Supplemental Information for Change Order No. 70-8

8. ANSC Letter 7120:7338, dated April 24, 1970, J. L. Dooling to A. C. Sanderson (WANL); Subject: Subcontract NP-1 Change Order W70-8 (SNPO-C Change Order 70-14)

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TITLE Structural Support Coolant Assembly Evaluations
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ABSTRACT

This report discusses SSCA requirements under normal and malfunction conditions, leading to permissible leakages, valve rates, and emergency procedures.

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or Cut

Fold
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